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NUTRITIONAL DISORDERS IN ALKALINE SOILS AS CAUSED BY DEFICIENCY OF CARBON DIOXIDE

By

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and

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BY J. F. BREAZEALE AND W. T. MCGEORGE

INTRODUCTION

Intensive investigations conducted in this laboratory during the past several years upon the chemical and physical characteristics of the alkaline, calcareous soils of Arizona, (11, 12, 13) have led us to believe that soil chemists are laying too much stress upon chemical solubility studies, and have given too little attention to the influence of the many and varied soil conditions which the crop must combat for its food supply. It has been observed repeatedly by the authors, that crops often suffer from phosphate deficiency when grown upon alkaline soils, although the soil solution may contain many times as much soluble phosphate as is necessary for the normal development of the plants. This is true of nitrate also, but probably to a lesser extent. Either of these two plant foods, phosphate or nitrate, may easily become the limiting factor in crop yields.

It has become apparent, at least under Southwestern conditions, that plant food absorption may not be correlated, necessarily, with the amount of plant food which is dissolved in the soil solution. In other words, there is a difference between solubility and availability, and a plant food, phosphorus for example, may be in solution and yet not be available to plants.

It often has been observed by many of the investigators who have studied arid soils, that "a little alkali is entirely too much." That is, the apparent toxicity is equally in evidence whether large amounts or only traces of black alkali are present in the soil. In view of the characteristic dispersed or puddled condition of such soils, their infertility has been explained, in part, on the basis of their poor physical condition. So far as we know few, if any, have noted or commented upon the absence of carbon dioxide in black alkali soils. Still another existing factor which has been overlooked is that the hydroxyl ions present in alkaline soils interfere with the absorption of plant food by the crop. When carbon dioxide is not present in the soil, or is not found dissolved in the soil solution, a deficiency of available phosphate exists. But no matter how much phosphate is present in the soil solution, if hydroxyl ions are present, the crop will suffer from phosphate starvation. In other words, while the hydroxyl ion is an active agent for solution of soil phosphate, it exerts a depressing effect on its availability, that is, upon the absorption of phosphate by plants.

The work which will be reported in this bulletin was undertaken in the hope of explaining this apparent inconsistency, namely that of a plant suffering for food when in the midst of plenty.

SOME ASPECTS OF THE PROBLEM

In the previous studies which we have conducted, three facts are outstanding: First, that many soils will respond to applications of soluble phosphate regardless of the fact that their soil solution is relatively well supplied with phosphate ions; in other words, at pH 8.5 or higher, there is, with few exceptions, an abundance of soluble phosphate in the soil solution; second, that plants are unable to absorb their required amount of phosphate from that present in the soil solution of alkaline soils; and third, that in many such soils, free carbon dioxide is absent. It is of interest to discuss these three points in some detail.

1. With the exception of soils whose reactions fall within the range pH 8.0 to 8.5, our soils are fairly well supplied with soluble phosphate. Below pH 7.5 the solvent action of carbon dioxide comes more readily into play, and above pH 8.5 the solvent action of hydroxyl ions is very marked. The question naturally arises as to the value of this alkaline-soluble phosphate. In our own experience we have yet to find an alkaline soil, that is, one of pH 8.5 or higher, which did not possess relatively large amounts of water-soluble phosphate, yet many of these same soils respond to phosphate fertilization. The solubility of phosphate in alkaline solutions has been recognized in soil studies for many years, and this property is often utilized as a means of determining what has been assumed to be, the available phosphate in soils. The soils are usually extracted with monovalent hydroxide solutions of definite strength, for definite periods of time, and the solubility of phosphates correlated with growth. While it is barely possible that such data may be correlated with crop response, our studies cast serious doubt upon the nutritional value of alkaline-soluble phosphate in calcareous soils, unless the alkalinity of the soil is corrected.

The effect of reaction (11, 14) on phosphate solubility has been dealt with in previous publications. Iron and aluminum phosphates were shown to be more soluble under alkaline than under acid soil conditions. Calcium phosphates, while much less soluble at alkaline reactions as compared to acid, are more soluble when alkalinity is due to sodium hydroxide than where it is due to calcium hydroxide. This leads up to the question of plant food solubility, and its absorption under alkaline soil conditions.

2. The fact that alkaline calcareous soils, which are well supplied with soluble phosphate, will respond to phosphate fertilization, shows that phosphate starvation in alkaline soils is not directly a chemical problem in solubility, but rather a physiological problem in absorption. It is true that the ionization of orthophosphate is closely associated with soil reaction, the H_2PO_4 ion being the predominant ion in acid soils, and the HPO_4 ion being the predominant ion in alkaline soils, with the two being present in equal proportions at near neutrality, pH 6.8, and the PO_4 ions being practically absent from the system at all times. When one compares the ionization of orthophosphate with the apparent phosphate deficiencies of alkaline soils, he is struck by the suggestion that there exists a plant preference for the H_2PO_4 ion, as plants show no phosphate starvation on many acid soils, which contain far less phosphate than do our best alkaline, calcareous soils which exhibit phosphate deficiency. The only other alternative is that hydroxyl ions seriously interfere with the absorptive processes of the plant. Preliminary studies on this phase of phosphate nutrition in alkaline soils have been presented already, (11) but will be given in greater detail in this bulletin.

3. The presence or absence of carbon dioxide is by far the most vital factor in controlling the fertility of Southwestern calcareous soils. We have shown that, in these soils, a close relation exists between water penetration, aeration, bacterial activity, carbon-dioxide formation and phosphate availability (13). Under different conditions, one or more of these factors may become a limiting one in crop production. In fact, it is often difficult to determine just which is the limiting factor. The absence of phosphate in the soil solution of soils below pH 8.5 is usually due to the absence of free carbon dioxide. This gas is formed largely by the respiration of soil bacteria and plant roots, which in turn depend upon good aeration and water penetration into the soil. Without these there can be little or no aerobic bacterial growth or root development. The absence of free carbon dioxide is exactly what should be expected under such soil conditions as are found in dispersed, alkaline soils. The soil solution of many of our soils is sufficiently alkaline to give a red color with phenolphthalein. At this pH, 8.5 or higher, there are hydroxyl ions in solution. It is a self-evident fact that there can be no free carbon dioxide in equilibrium with hydroxyl ions in the soil solution, and as will be shown later, it is equally evident that the absorptive processes of

the plant roots will be reduced to a minimum under such an environment. At soil reactions below pH 8.5, especially 8.0 to 8.4 inclusive, we find a range of minimum phosphate solubility. This is due largely to the absence of free carbon dioxide and the effect of solid-phase calcium carbonate and soluble calcium bicarbonate upon the dissociation of the difficultly soluble carbonato phosphate of calcium, which is the principal form of phosphate present in our soils.

EXPERIMENTAL PROCEDURE

It was evident that sand or soil cultures were not suited to the study of such a problem and for this reason, water cultures were used throughout this investigation. In most part, wheat seedlings were used as indicator plants, largely because of their adaptability, but, in some cases, the experiments were repeatd with corn, barley, and tomatoes.

The wheat seeds were soaked for several hours in water, then sprinkled on large, perforated aluminum discs which were floated in pans of water, to permit germination. When the plumules had reached a height of about 2 centimeters, they were removed carefully, one at a time, and replanted to smaller aluminum discs, in lots of 100 plants per pan. This procedure eliminated all the unsprouted seeds from the experiment. The smaller discs were about 7 inches in diameter, and these were floated in porcelain-lined pans holding one liter of culture solution, by means of short lengths of sealed, glass tubing. The barley and corn seedlings were treated in the same way, while the tomatoes were started in sand and later transferred to nutrient solutions. For transpiration measurements the seedlings were grown in wide-mouthed, liter bottles, in lots of 25 plants each.

In some few experiments, distilled water was used in preparing the culture solutions. This medium proved to be more or less unsatisfactory, for which reason tap water was used in most of the experiments. This tap water is pumped from a deep well under the building, and has the following composition.

TABLE 1.—ANALYSIS OF TAP WATER FROM THE UNIVERSITY OF ARIZONA.

Total solids	285 p.p.m.
Bicarbonate (HCO_3)	168 p.p.m.
Chlorine (Cl)	21 p.p.m.
Sulphate (SO_4)	75 p.p.m.
Nitrate (NO_3)	10 p.p.m.
Calcium (Ca)	50 p.p.m.
Magnesium (Mg)	6 p.p.m.

It will be seen that the salts in the water consist largely of calcium bicarbonate and calcium sulphate, that is, it is a "hard water." It has been our experience that ground water, spring, or well water, is the most suitable medium for plant growth where one expects to get vigorous, healthy plants in water cultures. Ground water itself is a soil solution, or soil extract, and as such, it should be in equilibrium with the constituents of the soil through which it has passed, and, it should contain traces of a great many elements which are now considered necessary in plant nutrition. Distilled water is, at best, an unnatural medium for plant growth, and often may prove toxic unless filtered through carbon black, or otherwise purified.

The tap water of the laboratory is derived from a calcareous substratum beneath a caliche layer about 30 feet in thickness. It is practically free of phosphorus, as is shown by lack of color development by the Deniges method. When phosphate, in excess of 5 parts per million of PO_4 is added to the water, a precipitation of calcium phosphate takes place. By experiment it was found that at pH 9.0 this water will retain practically 5 parts per million of PO_4 in solution, so throughout the investigations care was taken always to use concentrations of phosphate below this saturation point. While the tap water contained no detectable amounts of phosphate, it did contain a measurable amount of nitrate.

Throughout this work the plant was accepted as the last referee, and all conclusions were drawn according to plant response. While only representative data are presented, it should be explained that this work occupied many months, and scores of replications were made. The procedure followed was to repeat the experiments over and over, with improvements and variations in technique, in order to assure ourselves that no misinterpretation of plant response, or reaction, had been made, and that our conclusions were correct. Under the very best conditions and technique there is a wide variation in plant behavior, so the probable error was reduced to a minimum by using a large number of plants in each culture, and by running the experiments in duplicate or triplicate. Often cultures were placed under the same conditions with respect to temperature, position, and concentration of nutrient solution, and sets of plants with uniform rates of absorption were then selected for a series. Probable errors were also avoided in an experimental series by repeating the experiment over a period of several days or a week, and shifting the sets of plants from one treatment to another. For example, in one experiment, culture pans containing 100 plants each were placed under observation, numbers 1 and 2 in a nutrient solution of pH 9.0, and numbers 3 and 4 in a solution of pH 6.0. The rates at which phosphate and nitrogen were absorbed were determined. On the next day, plant cultures 1 and 2 in nutrients of pH 9.0 were shifted to the culture solutions maintained at pH 6.0, while plants in 3 and 4 were changed to nutrients of pH 9.0. On the following day they were again shifted.

This procedure practically eliminates any source of error, and is extremely satisfactory.

While, in some cases, the plants were analyzed to measure the magnitude of absorption, in most cases absorption was measured by analyzing the nutrient solution. In measuring the rate at which the plant foods were absorbed by the plants, aliquots of nutrient solutions were withdrawn from the culture bottles at definite intervals of time. Nitrate was determined by the phenoldisulphonic acid mehod, and phosphate was determined by the Deniges, or molybdic-blue, method. This method is admirably adapted to studying the absorption of phosphate by plants from culture solutions. In fact, such an investigation as that presented here, would be practically impossible without the Deniges method. While the method is very reliable, a few sources of error in culture work may be mentioned. After the plants reach a certain age, particles of roots will often "slough off," and when these are withdrawn in the aliquot, the phosphate contained in these particles of roots will induce high results. If the cultures are allowed to become too warm, either from sunlight or other source of heat, especially when working with nutrient solutions of high pH, the nutrient solution will take on a brown color, which interferes with the development of the molybdic-blue color, and the blue color will fade rapidly after development.

pH AS AN EXPRESSION OF SOIL ALKALINITY

Several years ago the authors observed that sodium hydroxide, rather than sodium carbonate, is the cause of alkalinity in most black alkali soils (5). Our subsequent investigations have confirmed this observation, and have shown that even hydrolyzed sodium zeolite is present only in very small amounts. The abnormal stress under which plants labor in alkaline soils is due directly to the hydroxyl ions. These are formed by the hydrolysis of the sodium zeolite. The effect of the hydroxyl ion is not as one of toxic concentrations, such concentrations being rarely present, but rather as a depressing influence of the hydroxyl ion on plant food absorption.

The methods now used for the determination of black alkali in alkaline soils are admittedly faulty. A soil is shaken with water, usually one part soil to five parts water, and this solution is filtered and analyzed. The dilution procedure of this method, in itself, permits hydrolysis of the alkaline sodium compounds beyond that possible in the soil *in situ*, and on analysis of this soil extract, the method yields an exaggerated value for total alkalinity, which is usually calculated as sodium carbonate. In other words, the amount of alkali determined by present methods fails to tell one the actual amount of alkalinity in the soil solution:

How this can be determined, and how best to represent soil alkalinity, is of special interest to all students of alkaline soils. It occurred to us that it would be a worthwhile contribution to calculate the true amount of alkaline materials present in soil solutions within the pH range covered by alkaline soils.

The hydroxyl-ion concentration is the damaging constituent of alkaline soils. It is self evident that the amount of hydroxyl ions present will depend upon the reaction, pH, as this is governed by the concentration of hydroxyl ion. It is evident also that the concentration present will be substantially constant for all soils of similar reactions. Thus, if one knows the amount of hydroxyl ions present in the soil solution, the pH in other words, the amount of sodium hydroxide or sodium carbonate which can be present may be calculated from the ionization constants and degree of hydrolysis of these compounds. Such calculations will yield the true amounts of these two alkali salts which are present in the soil solution. It is recognized that the degree of ionization of these salts will be affected greatly by the presence of neutral salts, such as sodium chloride or sodium sulphate, and that the calculations will give only the amount of ionized sodium hydroxide, or sodium carbonate, which can be present. But since it will be shown that hydroxyl ion, through its influence on plant food absorption, is the only factor in which we are interested, it will not be necessary to complicate our calculations at this time by allowing for neutral salts present.

Another purpose in assembling these data is to present information which should assist the layman and many soil workers to evaluate the term pH which is so extensively used in expressing soil reaction. The use of this term has been severely criticized at times, and justly so, because of its failure to present in specific or understandable terms the actual concentration of alkali or acid. The data given in Table 2 should help to clarify the terms used in expressing soil alkalinity. These data are shown graphically in Figure 1.

Column 1 gives the pH values, and column 2 the pOH values, the latter of which is less used than the former. In column 3 the relative alkalinity is expressed in terms of specific alkalinity, a term suggested by Wherry (16). It has the advantage of showing at a glance that a difference of one pH unit, proceeding up the scale, represents a difference of 10 times the hydroxyl ion concentration. That is, a soil of pH 10.0 will contain 10 times as many hydroxyl ions as a soil of pH 9.0 and 100 times as many as a soil of pH 8.0. Columns 4 and 5 represent the actual concentration of hydrogen and hydroxyl ions present. At pH 7.0, or neutrality, there are equal amounts of the two ions present, and with increasing alkalinity the hydroxyl ions increase and the hydrogen ions

TABLE 2.—SHOWING RELATION BETWEEN pH, pOH, SPECIFIC ALKALINITY, PARTS PER MILLION OH, PARTS PER MILLION NaOH, AND PARTS PER MILLION Na_2CO_3.

pH	pOH	Specific alkalinity	Concentration oH ion	Concentration H ion	P.p.m. OH ion	P.p.m. NaOH	P.p.m. Na_2CO_3
7.0	7.0	1.0	10^{-7}	10^{-7}			
7.2	6.8	1.6			.0016	.0036	
7.4	6.6	2.5			.0025	.0057	.006
7.6	6.4	4.0			.0040	.0092	.014
7.8	6.2	6.3			.0063	.0145	.031
8.0	6.0	10.0	10^{-6}	10^{-8}	.0100	.023	.066
8.2	5.8	16.0			.0160	.036	.092
8.4	5.6	25.0			.0250	.057	.150
8.6	5.4	40.0			.0400	.092	.247
8.8	5.2	63.0			.0630	.145	.397
9.0	5.0	100.0	10^{-5}	10^{-9}	.1000	.23	.635
9.2	4.8	160.0			.1600	.36	1.050
9.4	4.6	250.0			.2500	.57	1.740
9.6	4.4	400.0			.4000	.92	2.870
9.8	4.2	630.0			.6300	1.45	4.620
10.0	4.0	1000.0	10^{-4}	10^{-10}	1.0000	2.30	7.450

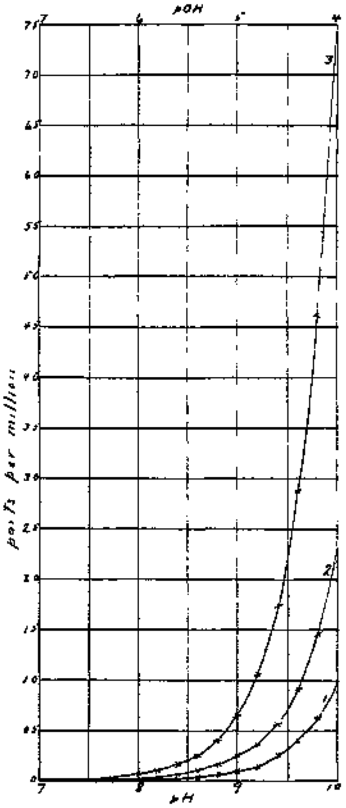

Fig. 1.—Showing relation between pH, pOH, and parts per million (1) hydroxyl ion, (2) sodium hydroxide, and (3) sodium carbonate.

decrease. In column 6 we have given the actual amount of hydroxyl ions in parts per million of solution, which will be present at the respective pH. In column 7 we have given the actual amounts of sodium hydroxide, in parts per million, which are necessary to produce reactions of definite pH. In making these calculations, sodium hydroxide was assumed to be ionized completely. In column 8 we have given, in parts per million, the actual concentrations of sodium carbonate which are present at different pH values. In making these calculations, sodium carbonate was assumed to be hydrolyzed completely at the concentrations which would be present at 7.2, and hydrolyzed at only 83 percent at concentrations prevailing at pH 10.0. The actual amount of hydroxyl, sodium hydroxide, or sodium carbonate present at all pH values between pH 7.0 and 10.0, is quite illuminating. At pH 10.0, for example, there is present 1 part per million hydroxyl ion, 2.3 parts per million sodium hydroxide, or 7.45 parts per million sodium carbonate, all of which concentrations have been shown to be well within the limit of tolerance of wheat plants. The data given in this table emphasize the function of soil reaction in ion absorption, and stamp pH, in its relation to ion absorption, as being the most important growth-limiting factor in alkaline soils. The data, alone, are almost positive proof that the concentration of sodium hydroxide or sodium carbonate present in alkaline soils, is not of sufficient magnitude to explain their infertility upon the basis of direct toxicity. It is evident that the influence of hydroxyl-ion concentration upon plant food absorption is the real cause of infertility in black alkali soils.

INFLUENCE OF pH ON ABSORPTION OF PHOSPHATE BY PLANTS

In studying the influence of pH on the absorption of phosphate by plants, many experiments were conducted, and each experiment repeated several times. This was necessary because of our desire to secure data from as many conditions as possible. That is, in such an experimental procedure as we followed, namely, determining the changes in phosphate-ion concentration of the nutrient solution, variations in feeding habits are met. For reasons unknown to us, some days were more active feeding days than others. Then again, while plants of the same age were always used in an individual series, the age of plants in separate series was not always the same. Day and night temperatures also varied greatly. But with all these variations in environment, and their effect upon the feeding rate, the relative effect of pH in each series, without a single exception, followed the same trend. In view of this, for the sake of brevity, only representative experiments will be presented.

In all experiments the concentration of phosphate in the nutrient solution was kept below 5.0 parts per million partly because, under soil conditions, the concentration of the soil solution is rarely found above this, as well as on account of the calcium content of the tap water, as previously mentioned.

The culture solutions, for the following experiment, were prepared from tap water to which was added 4.2 parts per million of phosphate, calculated as PO_4[*] ion. Phosphate was added in the form of Na_3PO_4. The reaction of the tap water was pH 7.4. One culture was reduced to pH 4.8 and another to pH 7.0 with hydrochloric acid, a third was increased to pH 9.0 with sodium hydroxide, and a fourth culture prepared by reducing one of the pH 9.0 culture solutions to pH 6.8 with carbon-dioxide gas. One hundred wheat seedlings were grown in one-liter volumes of each of these culture solutions, and the amounts of phosphate absorbed were determined by analyzing the extracts at the end of 24 hours. In the following table are given the original and final pH of the culture solution, and the original and final phosphate concentration.

TABLE 3.— EFFECT OF pH UPON THE ABSORPTION OF PHOSPHATES.

	pH of culture		PO_4	
	Original	Final	Original	Final
1	4.8	5.0	4.2	1.4
2	7.0	7.0	4.2	1.4
3	9.0	8.0	4.2	3.8
4	6.8*	6.8	4.2	1.8

* Reduced from pH 9.0 by CO_2 gas.

It will be noted that the reaction of cultures 2 and 4 remained unchanged, while the pH of 3 was decreased, and that of 1 increased, both tending toward neutrality, and indicating this to be the optimum reaction for absorption of phosphate. Attention is called to the fact that, where the reaction of the culture is reduced by carbon dioxide, the absorption of phosphate is very active. The experiment clearly demonstrates that absorption of phosphate at alkaline reactions is reduced either to zero or to insignificant proportions. The rate of diffusion of ions in nutrient solutions, as well as the neutralizing effect of carbon dioxide from the plant roots, makes it very difficult to determine the exact "dead

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[*] Throughout this bulletin phosphate concentration is expressed as PO_4 ion and all calculations made on the basis of this ion because it is in most common use. In reality, as we have shown by calculation from ionization constants, the phosphate is present in the culture solutions and absorbed as H_2PO_4 or HPO_4 ions, depending upon the reaction of the solution. PO_4 ion is practically absent from the system.

line" for phosphate absorption. Many culture experiments were conducted in which the culture solutions were analyzed for phosphate and pH at hourly intervals, and these experiments showed that, where conditions are closely controlled, phosphate is not absorbed by the roots until the plant has reduced the pH to at least pH 7.6. In fact, we feel justified in stating that the plant will not absorb phosphate as long as the contact zone of the root is pH 7.6, or higher.

The amounts of phosphate used are admittedly very small, and the differences between culture solutions very slight, often less than 1 part per million of PO_4, but these differnces are real and consistent, and of appreciable magnitude when one is familiar with the minute traces in soil solutions from which the crop is nourished in nature. Above all, these small amounts of phosphate can be determined with extreme accuracy by the Deniges method, within 0.1 part per million, when working on a concentration of less than 5.0 parts per million.

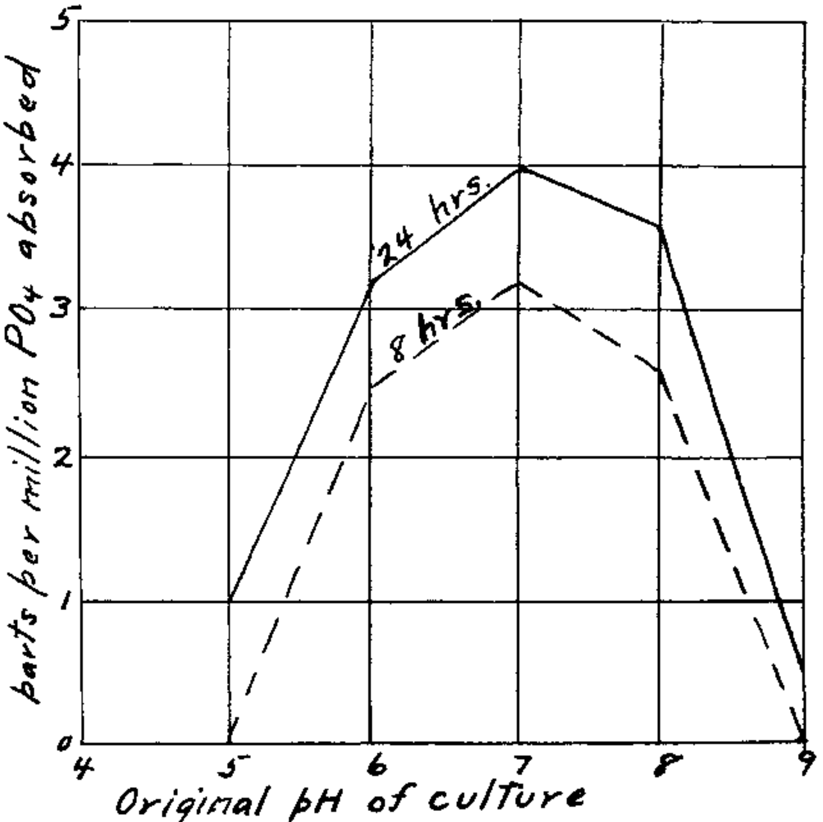

Fig. 2.—Showing relation between pH of culture solution and absorption of phosphate at 8- and 24-hour periods.

The data from another experiment, illustrating the relative feeding power at different reactions, are shown graphically in Figure 2.

ABSORPTION OF PHOSPHATE IN THE PRESENCE OF NITRATE AND POTASSIUM

The preceding experiments having been conducted with tap water, several additional series were conducted in which nitrate and potassium in addition to phosphate were added to the tap water. Five parts per million each of nitrate and potassium, as sodium nitrate and potassium chloride, were added to the culture solutions, in addition to 4.2 parts per million PO_4. The absorption of phosphate over a period of 24 hours is given in Table 4.

TABLE 4.—THE EFFECT OF pH ON THE ABSORPTION OF PHOSPHATE IN THE PRESENCE OF NITRATE AND POTASSIUM.

	Original pH	P.p.m. PO_4	
		Original	Final
1	4.5	4.2	1.5
2	7.0	4.2	0.8
3	9.0	4.2	3.4
4	6.5*	4.2	0.3

* Reduced from pH 9.0 by passing CO_2 gas through the culture solution before placing the plants in it.

This experiment was repeated on several days in succession, shifting the plants from one reaction to another, with no change in the relative feeding rate. This indicates that the difference in the rate of phosphate absorption is due to the reaction of the culture solution, and not to any peculiarities of the plants. We have also obtained the same results in distilled water to which only sodium phosphate was added.

ABSORPTION OF PHOSPHATE BY PLANTS AT ACID REACTIONS

Having shown that little or no phosphate absorption takes place at reactions above pH 7.6 * except where diffusion of carbon dioxide is rapid enough to reduce the pH in the root-contact zone to a point less than this, the question arose as to the comparative absorption of phosphate at acid and neutral reactions.

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* It will be noted in many of our tables that absorption from culture solutions has taken place when the pH of the entire solution was still above pH 7.6. This is due to the fact that the carbon dioxide exuded by the roots reduced the pH of a thin film of solution in immediate contact with the roots before diffusion of the carbon dioxide into the culture as a whole. Our data represent the culture solution as a whole which was thoroughly stirred only when aliquots were removed for analysis.

Culture solutions were prepared with tap water to which 2.4 parts per million PO_4 were added, and adjusted to reactions pH 7.5, 7.0, 6.0, 4.5. Wheat plants were grown in this series, and aliquots removed at 2-hour intervals for determination of phosphate concentration and pH. This experiment was repeated six times, starting out each day with a fresh nutrient solution, and shifting the plants in order to avoid differences in plant behavior. From these six experiments, the data given in Table 5 is taken as representative of the absorption by the plants at these different hydrogen-ion concentrations.

TABLE 5.—EFFECT OF NEUTRAL AND ACID REACTIONS UPON THE ABSORPTION OF PHOSPHATES.

	Original pH	pH of nutrient culture				Original PO_4	Concentration of nutrient			
		2 hrs.	4 hrs.	6 hrs.	8 hrs.		2 hrs.	4 hrs.	6 hrs.	8 hrs.
1	4.0	5.0	5.8	6.0	6.2	2.4	2.2	2.0	0.8	0.5
2	6.0	6.6	6.6	6.6	6.8	2.4	2.3	2.0	0.8	0.5
3	7.0	6.9	6.9	6.9	6.9	2.4	2.3	1.5	0.7	0.3
4	7.5	7.4	7.4	7.3	7.2	2.4	2.4	1.9	1.7	0.8

It will be noted from these data that the plants absorbed phosphate quite rapidly from all these cultures, but nevertheless there is a slight difference in favor of the plants growing in the cultures of neutral reaction. This trend was observed in all the separate series conducted in these experiments. From the manner in which the plants have acted to reduce the acidity of the cultures to near neutrality, which caused a slightly more rapid absorption at pH 6-7, there is much evidence that the plant prefers this reaction. In other words, this is the range of plant economy, and the experiment demonstrates the vital forces which the plant exercises in effecting its economies.

ABSORPTION OF PHOSPHATE FROM THE PHOSPHATES OF SODIUM, POTASSIUM, AND CALCIUM

As the next step in our investigation it appeared advisable to study the absorption of PO_4 from different phosphate salts.

In the first experiment the comparative rate at which plants absorb phosphate from the phosphates of sodium, potassium, and calcium was determined. Nutrient solutions were prepared in duplicate, using tap water to which 2.0 parts per million PO_4 were added. The experiment was repeated four times, each at an interval of 24 hours, and phosphate determinations made in the culture solutions at 3-, 5-, 9-, and 24-hour intervals. The cultures were all adjusted to pH 7.0. The following data are presented as typical of the results obtained.

TABLE 6.— COMPARATIVE RATE OF PHOSPHATE ABSORPTION FROM SOLUTION OF CALCIUM, POTASSIUM, AND SODIUM PHOSPHATES.

	Original PO_4	P.p.m. PO_4 withdrawn by plants			
		3 hrs.	5 hrs.	9 hrs.	24 hrs.
Calcium phosphate........	2.0	0.48	0.98	1.08	All
Potassium phosphate....	2.0	0.40	1.05	1.00	All
Sodium phosphate..........	2.0	0.48	1.00	1.00	All

The data show that there is little or no difference in the rate at which wheat plants absorb phosphate from these three forms of phosphate when they are present in neutral solutions in equal amounts of PO_4 ions.

ABSORPTION OF PHOSPHATE FROM SOLUTIONS OF IRON AND ALUMINUM PHOSPHATES

In this experiment the comparative rate at which wheat plants absorb phosphates from solutions of the iron and aluminum salts was determined. In view of the solubility of iron and aluminum phosphates in solutions containing hydroxyl ions, it is probable that the phosphate present in the soil solution of our alkaline soils is largely the phosphates of these two bases. Culture solutions were prepared containing 2.4 parts per million PO_4 from these phosphates. The cultures were adjusted to reactions pH 9.4, 6.9, and 4.8. Wheat plants were grown in these cultures, and the solutions analyzed for pH and phosphate at 2-, 4-, 6-, 9-, and 24-hour periods, and the experiment repeated six times, using a fresh nutrient solution and shifting the plants each time. The following data are selected as typical of these six experiments.

TABLE 7.— CHANGE IN pH AND PO_4 IN CULTURE SOLUTIONS OF IRON AND ALUMINUM PHOSPHATES.

	Reaction (pH)						Concen. of PO_4 in culture					
	Original	2 hrs.	4 hrs.	6 hrs.	9 hrs.	24 hrs.	Original	2 hrs.	4 hrs.	6 hrs.	9 hrs.	24 hrs.
Aluminum phosphate	9.4	9.4	9.0	9.0	9.0	8.6	2.4	2.4	2.3	2.2	2.4	2.0
	6.9	6.9	7.0	7.0	7.0	7.0	2.4	2.3	1.1	0.6	0.5	0.0
	4.8	4.8	5.0	5.4	5.4	6.2	2.4	2.0	1.0	0.5	0.4	0.0
Iron phosphate	9.4	9.2	9.2	9.0	9.0	8.0	2.4	2.4	2.3	2.2	2.4	1.4
	6.9	6.9	6.8	6.9	7.0	7.0	2.4	1.4	1.1	0.5	0.4	0.0
	4.8	4.8	5.0	5.4	5.4	6.3	2.4	1.6	1.0	0.5	0.4	0.0

This experiment again shows that there is no absorption of phosphate in alkaline solutions, and that there is little difference between absorption from neutral and acid solutions. It also shows that the plants absorb phosphate at equal rates from solutions of iron or aluminum phosphates. It seems fair to conclude from this and the preceding experiment, that plants absorb phosphate ions at the same rate regardless of the nature of the base present in the salt.

CALCIUM CARBONATE AND PHOSPHATE ABSORPTION

As we have mentioned many times before, most of the cultivated soils of this State are calcareous, and this calcium carbonate is instrumental in forming a very insoluble carbonato-phosphate of calcium. The ionization of this phosphate compound may be reduced to zero, or nearly so, by the presence of an excess of calcium carbonate. Thus, no investigation of phosphate would be complete without some consideration of the role which calcium carbonate plays in whatever phase of the problem is under study. In the next experiment the effect of calcium carbonate on phosphate absorption has been studied.

A small amount of sodium phosphate was added to tap water and the whole boiled for 2 hours. It was then cooled, and filtered to remove the precipitated calcium phosphate. Carbon-dioxide-free air was then passed through the filtrate for 10 minutes, and the solution divided into two parts. Through one portion, carbon dioxide was passed until the pH had been reduced to 6.0. The other portion received no carbon dioxide. Each of these portions was then used as nutrient solutions, with 100 wheat plants to one liter of nutrient solution. The amount of phosphate removed by the plants over a 5-hour period is given in Table 8.

TABLE 8.—THE EFFECT OF CALCIUM CARBONATE UPON THE ABSORPTION OF PHOSPHATES, A.

	Reaction		PO_4 concentration	
	Original pH	Final pH	Original p.p.m.	Final p.p.m.
1. Water boiled and aerated with CO_2-free air	8.7	7.6	1.4	0.6
2. Same as 1	8.7	7.6	1.4	0.6
3. Water boiled and aerated with CO_2	6.0	7.0	1.4	0.3
4. Same as 3	6.0	7.0	1.4	0.2

The effect of carbon dioxide in reducing the pH of the culture solution, has been to increase materially the rate at which the plant absorbed phosphate from the nutrient.

In all the preceding nutritional studies, sodium hydroxide was used in producing the alkaline reactions of the culture solutions. In view of this, some experiments were conducted using calcium carbonate as a source of alkali. Aerated carbon-dioxide-free water was shaken with calcium carbonate, and the solution filtered. The pH of this filtrate was 8.6. Sufficient phosphate solution was added to liter volumes of this solution to produce a concentration of 2 parts per million PO_4. One hundred wheat plants per liter of culture solution were used. At the end of 5 hours the reaction and phosphate concentration of the nutrient solutions were determined. The results are given in the following table.

TABLE 9.—EFFECT OF CALCIUM CARBONATE UPON THE ABSORPTION OF PHOSPHATES, B.

	Reaction		PO_4 concentration	
	Original pH	Final pH	Original p.p.m.	Final p.p.m.
1. Distilled water saturated with $CaCO_3$	8.6	7.4	2.0	0.4
2. Same as 1, except CO_2 added	6.2	7.2	2.0	0.0

Attention is called to the rapidity with which the reactions of both solutions were changed to near neutrality, and the relative absorption of phosphate by the plants under the existing conditions. Again the vital role of carbon dioxide in alkaline soils is manifested.

When calcium carbonate is placed in contact with pure water, the salt is hydrolysed slightly, and at equilibrium, there are enough hydroxyl ions in the solution to give a pink color with phenolphthalein, which is closely pH 8.5. When carbon dioxide is introduced into the solution, the carbonate is changed to bicarbonate, and the final reaction is that of calcium bicarbonate, with a certain excess of carbon dioxide present, dissolved in the solution, or combined with water as carbonic acid, H_2CO_3. The association of these reactions with absorption of phosphate by plants in alkaline soils is self evident.

INFLUENCE OF REACTION (pH) UPON THE ABSORPTION OF NITRATES BY PLANTS

Having shown the intimate relation existing between the reaction of the nutrient medium and the absorption of phosphate, the question of a similar relation to the absorption of other ions arose. Some attention was therefore given to nitrates and potassium. The latter is reserved for future publication, along with other investigations on the potash requirements of alkaline soils. While nitrate cultures were conducted in many replications, the following will serve to illustrate the results obtained.

One hundred wheat seedlings were grown in liter volumes of tap water containing definite additions of phosphate, nitrate, and potassium. The reaction of the nutrient solution was first raised to pH 9.0 by addition of sodium hydroxide. The plants were grown in this solution, and others in the same solution after the pH had been reduced to pH 6.4

by addition of carbon-dioxide gas. Aliquots were withdrawn from the solutions at 5- and 10-hour periods, and the phosphate and nitrate concentration determined. The data are given in the following table.

TABLE 10.—EFFECT OF THE pH UPON THE ABSORPTION OF NITRATE AND PHOSPHATE, A.

	Reaction (pH)			Con. PO_4 p.p.m.			Con. NO_3 p.p.m.		
	Original	5 hrs.	10 hrs.	Original	5 hrs.	10 hrs.	Orig. inal	5 hrs.	10 hrs.
1. Nutrient pH 9.0	9.0	7.6	7.4	1.8	0.8	0.7	19.5	18.0	4.0
2. Nutrient reduced to pH 6.4	6.4	7.2	7.2	1.8	0.0	0.0	19.5	16.0	1.0

On the next day the plans were shifted, that is, the plants which had grown in nutrient pH 9.0 were grown in the nutrient of pH 6.4. The culture solutions were analyzed again with the results given in Table 11.

TABLE 11.—EFFECT OF pH UPON THE ABSORPTION OF NITRATE AND PHOSPHATE, B.

	Reaction (pH)			Con. PO_4 p.p.m.			Con. NO_3 p.p.m.		
	Original	5 hrs.	9 hrs.	Original	5 hrs.	9 hrs.	Original	5 hrs.	9 hrs.
1. pH 9.0 nutrient	9.0	7.5	7.2	2.0	0.8	Trace	15.0	13.5	4.0
2. pH 6.4 nutrient	6.4	6.8	7.2	2.0	0.3	Trace	15.0	8.5	0.0

It is clearly evident that an alkaline reaction greatly depresses the absorption of nitrate, just as it does the phosphate. Without the aid of carbon dioxide for reducing the pH of the root-soil contact zone in calcareous alkaline soils, there would be no absorption of nitrate by the plant. This is another illustration of the vital role of carbon dioxide in alkaline soils, and another of many reasons why we have stressed the value of this gas in the nutrition of crops on Southwestern soils.

EFFECT OF pH OF CULTURE SOLUTIONS UPON ABSORPTION, AS DETERMINED BY ANALYSES OF THE PLANTS

In order to show that disappearance of ions from culture solutions was as an absorption and not a precipitation, one experiment is submitted in which the plants were analyzed. Wheat and barley seedlings were grown for 2 weeks in tap water, then they were put into a nutrient solution of 10 p.p.m. each of nitrogen, potassium, and phosphorous, and kept under observation for 12 days. All solutions were first made up to pH 9.0, with NaOH, then one-half of the cultures treated with carbon-dioxide gas, until the pH was reduced to 6.6. The solutions were changed daily, and the pH adjusted twice daily. The analyses of 100 plants from each culture solution are shown in Table 12.

TABLE 12.—ANALYSES OF PLANTS GROWN IN CULTURE SOLUTIONS OF DIFFERENT pH.

		Gms. per 100 wheat plants		Gms. per 100 barley plants	
No.	pH	N.	PO_4	N.	PO_4
1.	9.0	.1980	.2029	.1488	.1312
2.	6.6	.2262	.2296	.2148	.1640

Analyses of the plants showed the same results that were obtained by analyses of the culture solutions, namely, the absorption of both phosphorous and nitrates is stimulated by the presence of carbon dioxide.

COMPARISON OF CARBONIC AND SULPHURIC ACIDS AS SOURCES OF HYDROGEN IONS

In plant feeding, the process by which the plant reduces soil reaction involves the secretion of carbon dioxide by its roots. Throughout our work we have been struck by the vital part which carbon dioxide secretion plays in plant economy. Full realization of this is perhaps due to the fact that under Southwestern soil conditions, with the possible exception of water, it is by far the greatest limiting factor, and the most difficult to control.

One experiment was conducted to determine the absorbing rate of phosphate by plants in presence of carbonic and sulphuric acids as sources of hydrogen ions Tap water culture solutions were prepared in the same manner as in previous experiments and, after adding 2 parts per million PO_4, the reactions were reduced to pH 6.6 using carbon dioxide in the one case, and with sulphuric acid in the other. Wheat plants were grown in these cultures, and PO_4 concentration determined at given intervals. The data obtained are given in the following table.

TABLE 13.—ABSORPTION OF PHOSPHATES FROM CARBONIC-ACID AND SULPHURIC-ACID SOLUTIONS.

	Concentration of PO_4 in cultures at					
	0	2 hrs.	4 hrs.	6 hrs.	8 hrs.	24 hrs.
	P.p.m.	P.p.m.	P.p.m.	P.p.m.	P.p.m.	P.p.m.
Carbonic acid	2.0	0.9	0.6	0.3	0.3	0.0
Sulphuric acid	2.0	1.2	1.0	0.9	0.8	0.0

This experiment indicates that the plants absorb phosphate more rapidly from carbonic acid solution cultures, than from sulphuric acid solution cultures.

COMPARATIVE ABSORPTION OF PHOSPHATE BY PLANTS IN LIGHT AND IN DARK

During the many experiments conducted in this study, variations in rate of feeding were noted on different days. Largely as a matter of curiosity, several series of cultures were grown in light and in the dark to determine if variations in light intensity would influence the rate of phosphate absorption.

The plants were grown in solutions containing 2.4 parts per million PO_4. One set of plants was placed on the window bench with western exposure, while the other set of plants was placed in a dark, closed cupboard under the window bench. The experiment was conducted for 4 days, shifting the plants, and adding fresh culture solutions each day. The cultures were kept at neutrality. The data from a representative day's run are given in the following table.

TABLE 14.—EFFECT OF LIGHT UPON THE ABSORPTION OF PHOSPHATES.

	PO_4 culture solution as p.p.m.				
	0	2 hrs.	4 hrs.	6 hrs.	8 hrs.
Light	2.4	2.2	1.1	0.6	0.5
Dark	2.4	2.4	2.0	1.1	0.8

This experiment shows that plants absorb phosphate more readily in light than in dark. This is in agreement with experiments published by Hoagland (7).

EXPERIMENTS WITH OTHER CROPS

Having used wheat plants throughout our investigations up to this point several other plants were selected for repeating some of the experiments. These included tomatoes, barley, and corn.

Tomatoes—Tomato plants were started in trays of sand, and when they had reached a height of about 10 cm., they were transferred to culture bottles holding 500 cc. each. The plants were allowed to grow for over a week in order for them to become adapted to the culture solutions, and to develop new feeder roots, then they were placed under observation. Usually eight plants were put into each culture, and five bottles were included in each treatment. Sodium phosphate was added to tap water in amounts shown in the table, and the entire solution first made up to pH 9.0 with sodium hydroxide. One-half of the culture bottles were filled with the solution, and carbon-dioxide gas was then passed into the other half of the solution until the pH registered 6.6. In Table 15 is shown the absorption at 6- and 24-hours' growth.

TABLE 15.— INFLUENCE OF pH ON ABSORPTION OF PO_4 BY TOMATOES.

	pH		Concentration PO_4 p.p.m.		
Culture	Original	Final	Original	6 hrs.	24 hrs.
1	9.0	8.3	1.2	1.0	1.2
2	9.0	8.2	1.2	1.0	Lost
3	9.0	8.0	1.2	1.0	0.9
4	9.0	8.2	1.2	1.0	0.9
5	9.0	8.7	1.2	1.0	1.0
6	6.6	7.0	1.2	0.4	0
7	6.6	7.0	1.2	0.7	0
8	6.6	7.0	1.2	0.4	0
9	6.6	7.0	1.2	0.5	Trace
10	6.6	7.0	1.2	0.9	Trace

The tomato, like the other plants, showed the same ability to reduce the pH of the nutrient solution. It was also evident that little or no absorption of phosphate could take place at pH 9.0, and that the presence of carbon dioxide reduced the pH and stimulated absorption.

In the next experiment are given additional data obtained with tomato plants, illustrating the effects of pH upon the absorption of PO_4 and NO_3 ions. The same set of plants was used, but numbers 1 to 5 were put into solution pH 6.6 and numbers 6 to 10 in solution pH 9.0. One part per million of PO_4, and 12 parts per million of NO_3, as sodium nitrate, were added to all solutions. The plants were placed in these cultures from 8:30 a.m. until 4:30 p.m., when it was found that the pH of the alkaline cultures had been reduced from 9.0 to 8.6. There was no change in the pH of the other cultures. The alkaline cultures were then made up to original volume, and enough sodium hydroxide added to bring the pH back to 9.0. The cultures were then allowed to grow over night. In Table 16 are shown the average results, after 24 hours in the solutions.

TABLE 16.—INFLUENCE OF pH ON ABSORPTION OF NO_3 AND PO_4 BY TOMATO PLANTS.

		P.p.m. PO_4		P.p.m. NO_3	
	pH	Original	Final	Original	Final
Cultures 6-10	9.0	1.0	1.0	12.0	12.0
Cultures 1-5	6.6	1.0	Tr.	12.0	Tr.

Apparently, if the alkalinity of a culture solution is maintained at pH 9.0 there can be no absorption of either phosphate or nitrate.

Corn—Corn lends itself very well to solution cultures. Seeds were germinated upon wet filter papers which were spread upon floating aluminum discs, and when the plumule was about 10 cm. tall, they were transferred to wide-mouthed, liter culture bottles, and allowed to grow for several weeks in tap water. When the root development was considered sufficiently strong, they were placed under observation. Six plants were grown in each bottle, and two bottles, or 12 plants, were used in each treatment.

In Table 17 is shown the absorption for different periods of time in solutions of pH 9.0, and in the same solution to which had been added enough carbon-dioxide gas to reduce the pH to 6.4.

TABLE 17.—INFLUENCE OF pH ON ABSORPTION OF PO_4 AND NO_3 BY CORN.

	pH		P.p.m. PO_4		P.p.m. NO_3	
	Original	Final 24 hrs.	Original	Final 24 hrs.	Original	Final 24 hrs.
1 and 2	9.0	7.6	2.0	0.4	19.5	3.0
3 and 4	6.4	6.6	2.0	0.0	19.5	0.0

The plants were now shifted, and the experiment repeated.

	pH		P.p.m. PO_4			P.p.m. NO_3		
	Original	Final 7 hrs.	Original	7 hrs.	11 hrs.	Original	7 hrs.	11 hrs.
3 and 4	9.0	7.8	2.0	0.8	0.7	19.5	18.5	14.0
1 and 2	6.4	6.8	2.0	0.4	0.0	19.5	4.0	0.0

Like all other plants with which we have worked, corn absorbs neither PO_4 nor NO_3 from solutions of pH 9.0. When the pH is reduced by carbon dioxide, absorption takes place rapidly.

TABLE 18.—INFLUENCE OF pH ON ABSORPTION OF PO_4 AND NO_3 BY BARLEY.

	pH		P.p.m. PO_4		P.p.m. NO_3	
	Original	Final	Original	Final	Original	Final
1st. period						
1	9.0	7.7	1.2	1.2	8.0	8.0
2	9.0	7.7	1.2	1.2	8.0	8.0
3	6.4	7.2	1.2	0.7	8.0	4.0
4	6.4	7.2	1.2	0.7	8.0	4.0
2nd. period						
4	9.0	7.4	1.0	1.0	17.0	9.0
3	9.0	7.4	1.0	1.0	17.0	9.0
2	6.4	7.2	1.0	.7	17.0	5.5
1	6.4	7.2	1.0	.7	17.0	5.5

Barley—Barley seedlings were grown for the periods shown in the table, in a full nutrient solution of pH 9.0, and in the same solution which had been treated with carbon-dioxide gas until the pH registered 6.4. In Table 18 are shown the results of 9 hours' growth, of 100 seedlings in 1 liter of solution. The cultures were then shifted, numbers 1 and 2 were placed in solution pH 9.0, while numbers 3 and 4 were put into solution pH 6.4, and the plants allowed to grow for another 9 hours.

EFFECT OF SALT CONCENTRATION ON ABSORPTION OF PHOSPHATE BY PLANTS

During our investigations on the solubility of phosphate in alkaline soils, it was observed that salt concentration usually reduced the solubility, or ionization, of phosphates. In view of this, some experiments were conducted in order to determine the effect of salt upon the absorption of phosphate by plants.

Sodium chloride—A large volume of nutrient solution was prepared from tap water by adding sufficient sodium phosphate to bring the phosphate concentration to 3.7 parts per million PO_4. From this nutrient a series of cultures was prepared containing from 500 to 4,000 parts per million of sodium chloride, and 100 wheat plants were grown in 1 liter of each of these solutions. Aliquots were removed from the cultures at given intervals, and the pH and phosphate concentration determined. This experiment was repeated many times, and the sets of plants shifted each time the plants were changed to fresh culture solutions. A representative series is given in the following table, all cultures being brought to neutrality.

TABLE 19.—EFFECT OF SODIUM CHLORIDE UPON THE ABSORPTION OF PHOSPHATES.

	Concentration of PO_4 in nutrient culture solutions				
	Original	3 hrs.	5 hrs.	9 hrs.	24 hrs.
1. No NaCl	3.7	2.0	1.3	0.50	Trace
2. 500 p.p.m. NaCl	3.7	2.0	1.2	0.56	Trace
3. 1,000 p.p.m. NaCl	3.7	2.0	1.4	0.80	Trace
4. 2,000 p.p.m. NaCl	3.7	2.1	1.4	0.76	Trace
5. 3,000 p.p.m. NaCl	3.7	2.2	1.4	1.00	0.15
6. 4,000 p.p.m. NaCl	3.7	2.6	1.5	1.10	0.18

This experiment shows that there is only a very small decrease in absorption of phosphate by concentrations of sodium chloride up to 4,000 p.p.m.

Sodium sulphate—The same experiment was repeated with sodium sulphate and the data obtained are given in Table 20.

TABLE 20.—EFFECT OF SODIUM SULPHATE UPON THE ABSORPTION OF PHOSPHATES.

	Concentration of PO_4 in nutrient cultures			
	Original	2 hrs.	5 hrs.	10 hrs.
1. No Na_2SO_4	3.7	2.0	1.20	0.3
2. 500 p.p.m. Na_2SO_4	3.7	2.4	1.32	0.4
3. 1,000 p.p.m. Na_2SO_4	3.7	2.48	1.70	0.64
4. 2,000 p.p.m. Na_2SO_4	3.7	2.56	1.84	0.70
5. 3.000 p.p.m. Na_2SO_4	3.7	2.20	1.84	0.70
6. 4,000 p.p.m. Na_2SO_4	3.7	2.48	2.00	0.60

Here again, while there is a distinct depression in absorption of phosphate with increase in concentration of sodium sulphate, it does not appear to be serious, at least under the conditions of the experiment.

Calcium chloride and Magnesium chloride—While sodium chloride and sulphate are the principal salts reaching high concentrations in alkaline soils, the experiment was continued to include the chlorides of calcium and magnesium. The effect of these is shown in the following table.

TABLE 21.—EFFECT OF CALCIUM CHLORIDE AND MAGNESIUM CHLORIDE UPON THE ABSORPTION OF PHOSPHATES.

	Concentration of PO_4 in nutrient cultures						
	Calcium chloride			Magnesium chloride			
	Original	5 hrs.	9 hrs.	24 hrs.	5 hrs.	9 hrs.	24 hrs.
Control	3.7	2.4	1.0	0.4	3.5	2.2	0.4
500 p.p.m.	3.7	2.4	1.0	0.4	3.0	2.1	0.3
1,000 p.p.m.	3.7	1.8	0.7	0.3	3.0	3.0	0.4
2,000 p.p.m.	3.7	2.0	0.9	0.7	3.0	2.0	0.4
3,000 p.p.m.	3.7	2.2	1.0	0.4	3.0	2.8	0.9
4,000 p.p.m.	3.7	2.9	1.0	0.6	3.0	2.4	0.5

These experiments indicate that salt concentration in amounts found ordinarily in alkaline soils does not materially depress the absorption of phosphate by plants. It is suggested, however, that over longer periods of time and in continuous contact with such concentrations of salt, an accumulative and injurious effect might develop.

INFLUENCE OF REACTION ON TRANSPIRATION OF PLANTS

Under arid conditions, with intense light, high temperature, and low humidity, plants transpire at an enormous rate. Experiments were therefore conducted to determine both the effect of pH upon transpiration, and the relation between transpiration and the rate of plant food absorption.

Several cultures of 25 wheat seedlings each were grown in wide-mouthed bottles, holding 1 liter each, in a nutrient solution containing potassium and nitrates, but no phosphates. The plants grew vigorously, and after 4 weeks the transpiration of the cultures was determined upon several days in succession. Three sets of plant cultures which transpired approximately the same, were selected. No. 1 was placed in tap water at pH 9.0, without the addition of nutrient salts. Number 2 was put in a nutrient solution containing nitrates, potassium, and phosphates, also at pH 9. The same nutrient solution was used in number 3, but the pH was lowered from 9.0 to 6.8 with carbon-dioxide gas. The cultures were then weighed, placed in the sunshine, and allowed to stand for 8 hours. The pH of the solution, the transpiration of the plants, and the amounts of phosphate remaining in the culture solution, were then determined.

TABLE 22.—EFFECT OF pH UPON TRANSPIRATION.

	pH		Transpiration in grams	P.p.m. PO_4 in solution	
	Original	After 8 hrs.		Original	After 8 hrs.
1	9.0	8.4	148.0	0.0	0.0
2	9.0	8.4	149.0	0.8	0.8
3	6.8	6.8	148.0	0.8	0.0

The plants were shifted into culture solutions of different pH, from day to day, and no matter what combination or shift was made, the results were practically the same. The transpiration of the plants was not affected by the pH of the culture solution, but there was no absorption of phosphate from solutions of pH 9.0, and the addition of carbon-dioxide gas always stimulated the absorption. This experiment shows first, that at pH 9.0, the plant transpires as freely as it does at pH 6.8, but does not absorb phosphate; and second, that there is no relation between rate of transpiration and rate of phosphate absorption. This agrees with Hoagland's findings that "transpiration and absorption take place independently" (*7*).

THE VALUE OF MANURE AS A SOURCE OF CARBON DIOXIDE IN ALKALINE SOILS

Since practically all our soils are calcareous, it seems fair to assume that the soil solution of these soils will be about pH 8.0, or higher, in reaction. In fact, out of several thousand soils examined in this laboratory, with few exceptions, the reactions have been above pH 7.8. If this condition should prevail indefinitely, crop plants could absorb neither phosphate nor nitrate. Evidence of this is often noted under field conditions where the roots are covered with a thin film of calcium carbonate. When such conditions are noted, the plants are usually showing distress from malnutrition. This is usually observed when soils have become dispersed, or when other conditions interfere with root elongation and carbon-dioxide generation. The first act of a plant, when introduced into a soil of pH 8.0, or higher, is to exude carbon dioxide, and thus lower the reaction to the range of absorption. The ability of the plant to maintain the optimum pH for maximum growth in an alkaline soil is quite limited, and such performance depends upon good aeration and drainage. In poorly drained or puddled soils, the plant will show distress from the inability of its roots to function in this manner. In some soils there is considerable organic matter present and, under proper conditions, the decomposition of this material will greatly increase the carbon-dioxide supply in the soil over that exuded by the roots. Southwestern arid soils rarely contain more than traces of organic matter, and due to this fact a greater burden is placed upon the roots than is true in humid soils. Thus it has become the practice throughout irrigated districts, to utilize all forms of organic matter for reclamation purposes. Manure, when it can be obtained economically, is without question the best amendment for dispersed, black alkali soils. The beneficial effect of an application of manure will not be discussed, except from the standpoint of its effect upon the reaction of the soil. It is interesting to mention at this point the work of Stephenson and Chapman (15) showing excellent penetration of phosphate on manured soils.

When dry manure is plowed into the soil, it absorbs water, and begins to decompose. This decomposition is brought about by bacteria, and in an aerated soil, carbon dioxide is produced. If black alkali, sodium hydroxide, is present, and if the pH of the soil solution is above 8.5, the carbon dioxide, if generated in sufficient amounts, will unite with the sodium hydroxide and form sodium bicarbonate, and the reaction will be reduced to near neutrality. The effect of this reaction is shown in the following experiment.

A nutrient solution was made from tap water to which 2.5 parts per million PO_4, along with an ample supply of nitrogen and potassium, was added. This was brought to a reaction of pH 9.0 with sodium hydroxide, and 1-liter portions of this nutrient solution were then treated as follows:

1. Aerated with carbon-dioxide-free air for 6 hours.
2. Aerated with ordinary air for 6 hours.

3. Aerated with air which was drawn through decomposing manure just before it was passed through the culture solution.

4. Aerated with a stream of carbon-dioxide gas until pH was reduced to 6.6.

A detailed description of the method used in preparing nutrient number 3 may be of interest. A wide-mouthed bottle (A, Fig. 3) was filled with moist, decomposing manure, and air drawn slowly through this, and then through the culture solution for 6 hours.

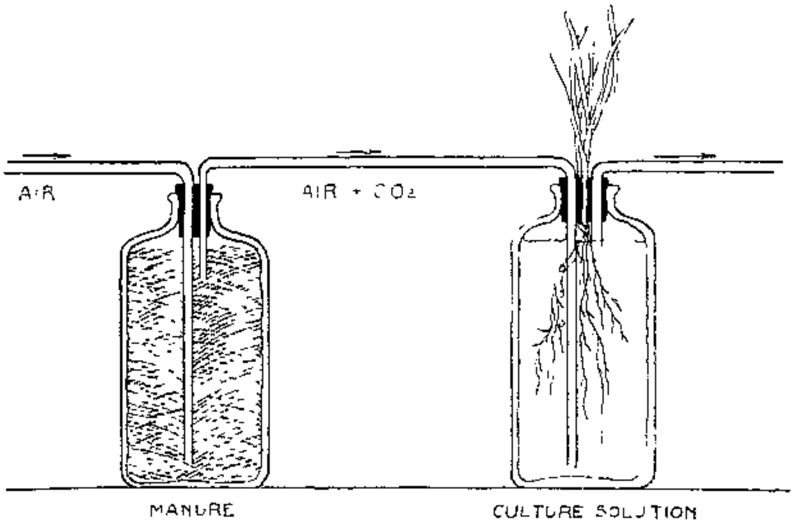

Fig. 3.—Showing method by which the carbon dioxide generated by decomposing manure was made to reduce the pH of an alkaline culture solution and thereby increase phosphate absorption.

One hundred wheat plants were put in each of the four nutrient solutions prepared as above, and placed in the sunshine for 1.5 hours. At the end of this period the phosphate concentration and pH of the nutrient solutions were determined. These data are given in Table 23.

TABLE 23.—EFFECT OF DECOMPOSING MANURE UPON THE pH OF THE SOLUTION AND UPON THE ABSORPTION OF PHOSPHATES.

	Reaction		PO_4 concentration	
	Original pH	Final pH	Original p.p.m.	Final p.p.m.
1. Aerated CO_2-free air	9.0	7.7	2.5	1.6
2. Aerated ordinary air	7.6	7.5	2.5	1.2
3. Aerated manure air	7.1	7.4	2.5	0.7
4. Treated with CO_2 gas	6.6	7.3	2.5	0.8

It is clearly evident from this experiment that manure is capable of assisting in the absorption of plant food by the plant and the manner in which it acts is demonstrated. In fact no matter what the source of carbon dioxide, its property of aiding phosphate and nitrate absorption always holds true.

In the preceding experiments, both commercial carbon dioxide and that derived from manure have been used. The value of this gas when generated by the plant itself is illustrated in the following experiment.

Two liters of tap water were made to pH 9.0 with sodium hydroxide and then divided into two parts. One liter was poured into a large culture pan, and a disc containing 275 wheat plants placed in it, and the plants allowed to remain for 3 hours. By this time the carbon dioxide given off by the roots had reduced the pH to 7.2. The plants were then removed, and 2.5 parts per million each of PO_4, N, and K were added to both portions, and 100 wheat plants placed in each culture for a period of 1.5 hours. The phosphate concentration, and pH were determined on the nutrient cultures at the end of this period. The results are given in Table 24.

TABLE 24.—EFFECT OF CARBON DIOXIDE WHEN GENERATED BY PLANTS UPON THE ABSORPTION OF PHOSPHATES BY OTHER PLANTS.

	Reaction		PO_4 concentration	
	Original pH	Final pH	Original p.p.m.	Final p.p.m.
1. Control	9.0	8.0	2.5	1.2
2. pH reduced to 7.2 by 275 plants	7.2	7.6	2.5	0.5

These results confirmed the observations which had been made before, namely, that no matter from what source carbon dioxide is derived, it has the same effect upon the absorption of plant food.

THE RELATION BETWEEN ROOT ELONGATION AND ABSORPTION OF PHOSPHATE AND NITRATE

Root elongation in water cultures is used often as a criterion of root vitality, or as an index of the limit of tolerance of the plant for culture solutions. The relation between elongation and absorption, that is, their comparative range of activity, was therefore studied.

In Technical Bulletin No. 36 of this series it was shown that absorption of phosphate ions, as well as root elongation, is a function of the enzymes which are present upon the root tip. If the enzymes are destroyed by a toxic base or acid, and root elongation is checked, phosphorus will not be absorbed. However, the absorption of nutrient ions ceases long before root elongation is checked by the creation of a toxic condition. This is shown in the following experiment.

Wheat seedlings were grown in tap water until their radicals were about 3 cm. long, they were then bound together in bunches of 12, with strands of cotton fiber, and the roots were then dipped into a thick magma of carbon black. This coated the roots permanently and any subsequent elongation could be detected. The plants were then put into solutions of different pH, as shown in Table 25, and allowed to stand over night. In the morning the growth during the night was measured, and is indicated in the table.

TABLE 25.—EFFECT OF pH UPON ROOT ELONGATION.

	pH		
1.	3.0	with H_2SO_4	No elongation, no root hairs.
2.	4.5	with H_2SO_4	Medium elongation, few root hairs.
3.	6.0	with H_2SO_4	Good elongation, many root hairs.
4.	7.4	untreated.	Good elongation, many root hairs.
5.	8.2	with NaOH	Good elongation, many root hairs.
6.	9.0	with NaOH	Fair elongation, few root hairs.
7.	10.0	with NaOH	Slight elongation, few root hairs.
8.	11.0	with NaOH	No elongation, no root hairs.

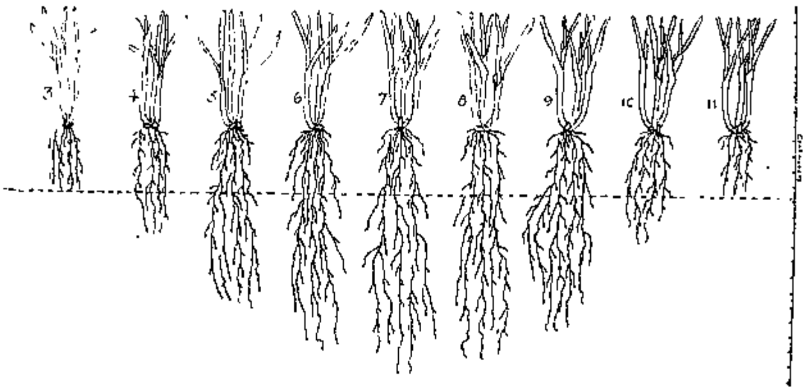

Fig. 4.—Showing relation between root elongation and reaction (pH) of culture solution. Numbers represent pH of culture and the dotted line represents length of roots at start of the experiment.

The appearance of the plants at the end of 24 hours is illustrated in Figure 4. The root growth above the dotted line represents the root system as it appeared before the plants were placed in the above solutions, and the growth below the line represents that which took place in the solutions of different pH. The maximum elongation was at about pH 7, or neutrality. There was some elongation in the solution of pH 4, and a fairly good growth in pH 9.0. The same tendency of the plants to reduce the pH of the alkaline solutions, and to raise that of the acid solutions, was shown, but the small number of plants and the large volume of solutions, made this error unimportant. This experiment was not meant to determine accurately the limit of tolerance of wheat for sulphuric acid or sodium hydroxide, but rather to show the relation between root growth and phosphate and nitrate absorption. At any rate, it is evident that a plant can grow, for a time at least, and can elongate its roots into a solution of pH 9.0 or higher, in a solution from which it cannot absorb either phosphates or nitrates.

A plant is but a product of environment, and during its age of adaptation must have met, and become accustomed to, a wide range of pH of the soil solution. An acid soil may run pH 4.0 or lower, while a black alkali soil often reaches pH 10.0. Such are the variations which a plant might have met during its era of development. If a crop plant, wheat for example, had been forced into a soil, or soil layer, of pH 9.0 during this era, and if it had not been able to endure this pH, it would have died and the species might have perished. As a matter of safety, a plant species, in its adaptation to alkali, must establish a tolerance far in advance of that with which it has come in contact. Only in this way could it survive. The most resistant plants are those which survive extreme stresses. That a plant can grow for a time in a soil from which it can not absorb necessary nutrient ions, is not surprising. It would be surprising if the reverse were the case, that is, if it could absorb nutrient material from a solution in which it could not grow. A plant always may be depended upon to act in the most reasonable and most economical way. If, for example, a plant with its roots growing down into a good soil, should strike a narrow dispersed layer of subsoil, with a high pH, the roots would not die, but would grow through the dispersed layer, and into the good subsoil beneath. Thus, in this case, as with the elongation shown at pH 9.0, the inherent character of the plant to survive unfavorable conditions for limited periods of time is apparent.

DISCUSSION AND SUMMARY

Under the soil and climatic conditions that exist in the Southwest, where all soils are calcareous and many of them contain alkali, where there is little rainfall and low humidity, several types of infertility tend to develop in the soil. Two of these types of infertility are caused directly by alkali. Alkali is classified, usually as white alkali, or the accumulation of neutral salts, sodium chloride or sodium sulphate in the soil, and black alkali, or the development of hydrolyzable salts of sodium, which form free alkali, OH ions, in the soil. Of the two, the latter type is more feared by the farmer. In both types, the injury to crops has been assumed by many to be due to the direct toxicity of the alkali on the plant. Several years ago the authors showed, in the case of black alkali, that crop injury could not be explained either upon the basis of the toxicity of the alkali, or upon its effect upon the structure of the soil. As our investigations have progressed, it has become more and more evident that the injurious effects of black alkali may be attributed largely to the effect of the alkali upon the absorption of plant food ions by the plant. We have shown that the amount of free hydroxyl ions, sodium hydroxide or sodium carbonate, which can be present at pH 9.0, for example, cannot be correlated with the injury which is shown by a plant when placed in a soil which has this reaction. We are convinced that the infertility of black alkali soils is due chiefly to the inability of the plant to absorb its food supply in the presence of hydroxyl ions.

Our investigations indicate that the presence of neutral salts, or the so-called white alkali, does not depress the absorption of nutrient material, unless the salts are present in toxic amounts. The injury which is caused by the concentration of neutral salts appears to be largely physical. It is very much like the effect of a dehydrating agent upon the cellular, vegetative structure. That is, it is more difficult for a plant to transpire, when it must draw its water from a concentrated salt solution than from a dilute salt solution.

While our experiments show that ion absorption is only slightly affected by the presence of neutral salts, it must be understood that the experiments were conducted over a period of not more than 24 hours. The accumulated effects which might follow if the plants were grown for longer periods of time in such salt concentrations, were not determined.

In previous work, Breazeale (1) found very little depression in the absorption of nitrate and phosphate in the presence of sodium chloride up to 1,000 parts per million. Sodium sulphate depressed absorption more than sodium chloride. The absorption of phosphates was more greatly depressed by these salts when calcium carbonate was present. Hoagland and Martin (10) also obtained evidence of reduced phosphate absorption in the presence of these two salts.

There has been much research devoted to the influence of alkaline reactions (hydroxyl ions) on plant growth, a small part of which has dealt specifically with ion absorption. The work of Hoagland and his associates stands out prominently in this field. We seriously doubt whether many other soil investigators have awakened, fully or even partially, to the real significance of this phase of plant nutrition, that is, to the effect of soil reaction upon the absorption of plant nutrients.

In 1912, Breazeale and LeClerc (4) demonstrated the depressing effect of alkaline reactions upon plant growth and upon the absorption of phosphate and nitrate ions. These investigators were handicapped by the lack of delicate quantitative methods of measuring hydrogen- and hydroxyl-ion concentrations, as well as by the lack of an accurtae colorimetric method for determining phosphorus. Hoagland being the first to apply electrometric methods to hydrogen-ion measurements in soils, early saw the application of these methods to studies in plant nutrition. Without reference to ion absorption, he studied the effects of hydrogen and hydroxyl ions on plant growth (6) and showed that, at the reactions represented by pH 8.2, hydroxyl ions were distinctly injurious, and at pH 9.4, they were extremely toxic. In subsequent studies (7, 8) in which he took up the absorption of ions, he showed that phosphate ions were absorbed in greater amounts in acid solutions than they were in alkaline solutions. The absorption of nitrate ions is illustrated by his work upon Nitella (9). On immersing cells of this plant in culture solutions of potassium nitrate, a penetration of nitrate ions into the cells took place readily at pH 5.6, less readily at pH 7.2, and practically not at all at pH 8.5.

From our investigations we feel that there is practically no absorption of either phosphate or nitrate at pH 7.6 or above.

It is self evident from the experiments just cited that the only natural process by which plants can feed in alkaline soils is through the agency of carbon dioxide. The source of this may be either the exudation of roots or the decomposition of organic matter and the latter is rarely present in appreciable amounts in arid soils. Thus the plant can absorb ions from only small limited zones of root-soil contact depending upon the rate at which the roots exude carbon dioxide and the speed with which it diffuses in the soil solution. As long as hydroxyl ions exist in the soil solution, carbon dioxide will be absorbed and neutralized by the hydroxide as soon as it diffuses away from the root zone. With these facts in mind one can not help but appreciate the paramount important of carbon dioxide in soil processes, and realize the little consideration which it has received in alkali-soil studies.

In the humid regions of the East, carbon dioxide is always present, both as a gas, CO_2, in the soil air, and as the acid radical, HCO_3, when dissolved in the soil solution. The carbon-dioxide content of the soil air in such regions is much higher than that of the overlying atmosphere. This is due to the fact that these soils contain organic matter, bacteria are active, and in the decomposition of the organic matter, large volumes of carbon dioxide are liberated. With an abundance of carbon dioxide always in the soil, it is quite natural that its importance in fertility should have been largely overlooked. In humid regions, it probably never becomes the limiting factor in crop production.

However, in the semi-arid regions, and on the reclaimed, irrigated, lands of the West, conditions are very different. Here carbon dioxide frequently becomes the *limiting* factor. All of our cultivated soils in Arizona are calcareous, and the percentage of calcium carbonate usually varies from 2 to 10 percent or more. Many of our soils also contain appreciable amounts of alkali, which is derived from the hydrolysis of sodium zeolite. These are commonly known as black alkali soils, and, although there may not be enough salt in the soil to appear upon the surface as a crust, it often does react with the soil solution to such an extent as to give an alkaline reaction of pH 9.0, or higher. If this reaction is maintained, there can be no carbon dioxide, either as a free gas in the soil air, or as a gas dissolved in the soil solution, in these soils. While all of our black alkali soils are calcareous, the reverse of this is not true; a soil may contain a high percentage of calcium carbonate, and no black alkali. Carbon dioxide can exist in a calcareous soil, when no black alkali is present.

When there is good aeration, and when organic matter is present, aerobic bacteria decompose the organic matter and generate carbon dioxide, which dissolves some of the calcium carbonate and forms calcium bicarbonate. However, in order to hold any considerable amount of calcium bicarbonate in solution, it is necessary to have a relatively large amount of carbon dioxide, free in the air, dissolved as the gas, or united with soil moisture as carbonic acid, H_2CO_3.

When calcium carbonate occurs alone with neither black alkali nor organic matter, the reaction of the soil solution will be near pH 8.5. Even at this reaction no free or dissolved carbon dioxide can exist in the soil.

We have shown that, even at a reaction of 8.5, there is no absorption of either phosphate or nitrate by ordinary crop plants. We have shown further, that, when carbon dioxide is introduced into the solution by the decomposition of organic matter, or otherwise, the pH of the solution is reduced to near neutrality, and absorption begins. When placed in a black alkali soil, the energy of the plant is exerted first in reducing the alkalinity of the soil solution by the exudation of carbon dioxide. Absorption of nutrient material begins only after the pH is reduced.

By reference to Table 2, it will be seen that, at pH 9.0, there is only one-fourth of one part per million of black alkali, sodium hydroxide, in the soil solution. The amount of carbon dioxide required to reduce this reaction to neutrality is therefore exceedingly small. It is almost unbelievable that such a small amount of alkali should prevent the absorption of plant food and equally as inconceivable that such an infinitely small amount of carbon dioxide should remedy the difficulty.

The difference of a few parts per million of carbon dioxide may mean a good crop or no crop whatever. Therefore, when a calcareous soil is in good tilth, even when it contains as much as 6 percent of calcium carbonate, we are likely to have enough carbonic acid present to reduce the pH of the soil from 8.5 to 6.5. We can have a decidedly acid reaction in the presence of an excess of calcium carbonate.

When calcareous soils are deficient in organic matter, or when aeration and water penetration are restricted, a reaction of pH 8.5 does exist in all parts of the soil except in the zone very close to the plant root. Here the exudation of carbon dioxide keeps the pH down to where the plant may absorb food. As far as the nutrition of the plant is concerned, the greater volume of the soil is useless, as the feeding zone is restricted to a few millimeters around the root. However, if organic matter is present and mixed into the soil, the evolution of carbon dioxide may be uniform throughout the soil mass, and the pH of the entire soil may be kept at neutrality.

It appears that, in Arizona at least, in a great many cases of crop failures, the immediate cause is the absence of carbon dioxide in the soil. The presence of carbon dioxide may be induced by aeration, cultivation, water penetration, and by the application of some kind of active organic matter or manure.

The deeper layers of soil, or the subsoil, seldom contain any organic matter, and at the same time there is little aeration. Aerobic bacteria do not live under such conditions, and there is no carbon dioxide formed. In calcareous soils, an alkaline reaction must exist in these lower levels, which quite likely prevents any absorption of nutrient materials. In all probability the tap roots of many plants are concerned with water absorption only and not with the absorption of plant food. Plants like wheat, will transpire water from a solution of pH 9.0, quite as freely as from a solution of pH 6.0.

As shown by Hoagland (8) a plant tends to adjust the reaction of the nutrient solution in the direction of its own sap. This is done either by absorbing the base or acid radical in the proper proportion needed to accomplish this purpose, or by the exudation of either basic or acid radicals, usually carbon dioxide. It has been shown by one of the authors (2) that a plant exudes carbon dioxide, or absorbs HCO_3 ions, depending upon the state of equilibrium between the plant and the nutrient solution. There is evidence that in maintaining equilibrium, there is an exchange of HCO_3 ions in the plant for NO_3 or H_2PO_4 ions in the outside solutions. This is the opinion of many plant physiologists; however, we have no clear evidence that the HCO_3 ion is exuded as such by the roots but rather that carbon dioxide, a product of respiration, is exuded, and this, in turn, becomes converted into the HCO_3 ions when dissolved in the water surrounding the roots. On this basis we are inclined to question the exchange theory in its entirety, and suggest that the process is not altogether an exchange of ions, for example, the NO_3 ion of the culture solution for the HCO_3 ion of the root. On the contrary it seems probable that the exudation of carbon dioxide by the root, and its subsequent conversion into HCO_3 ion, is merely the means by which the plant maintains an equilibrium of ions in the culture solution from which it may be absorbing positive and negative ions at different rates. It is probably the free carbon dioxide, and not HCO_3 ion exchange, which reduces the hydroxyl ion concentrations of the soil solutions of black alkali soils.

A plant is a great equalizer of forces, and under all conditions, in matters of nutrition, it may be depended upon to act in the most economical manner. It will always do the least amount of work, and expend the least amount of energy possible, in order to accomplish a given purpose. It has been shown by Buehrer, of this laboratory, that much more energy is required to absorb a plant food, phosphate for example, at pH 9.0, than at pH 6.5. Therefore in a well balanced, full nutrient solution, a plant like wheat will adjust the pH to a point where the most efficient absorption can take place. In our experience this is about pH 6.8. However, when only a single salt like sodium nitrate is present in the nutrient solution, at least two factors appear as stimuli. The demand for the acid radical, NO_3 is greater than that for the base, Na. If a plant is placed in a dilute nutrient solution of sodium nitrate, the NO_3 will be absorbed faster than the Na, and the pH of the solution will rise (1, 6). If the plant had no way of adjusting the reaction, absorption of NO_3 would either cease at about pH 7.5, or else the Na and NO_3 would be taken up in equivalent amounts. However, when the stimulus of the alkaline reaction is felt, the plant exudes carbon dioxide from its roots, which forms a solution of sodium bicarbonate. It is our experience that the pH of such a culture solution will be held fairly constant around 7.2, and that the absorption of nitrates will continue, although at a reduced rate.

In the case of potassium salts, potassium chloride for example, the opposite conditions prevail. When such a neutral salt is added to the culture solution, there is a greater demand for K than for Cl. The K will be absorbed faster than Cl, and the solution will become more and more acid until a state of equilibrium between the demand of the plant for potassium and the toxicity of the acid radical is reached. In our experience this is near pH 5.8.

Under certain conditions, a plant may exude one ion and absorb another, for example, calcium may be exuded by the root, and at the same time potassium may be absorbed in equivalent amounts. Such a process requires both an expenditure of energy and also the presence of an excess of either basic or acid ions in the plant sap. In such an exchange of bases as that just mentioned, the stimulus will be the greater demand of the plant for potassium than for calcium. Such an ionic exchange, whether of bases or acids, is not of the same nature as that when carbon dioxide is exuded, and the pH of an alkaline solution reduced. In the latter case, the stimulus is due partially to the reaction of the solution, and there may or may not be an absorption of plant food. Carbon dioxide is being formed continually during the ordinary processes of nutrition, and is being exuded by both leaves and roots. It is our experience that a plant will reduce the pH of an alkaline solution by the exudation of carbon dioxide, much more rapidly than it will raise that of an acid solution.

Under normal conditions of growth, a condition of equilibrium is maintained between the pH of the plant sap and that of the nutrient, or soil solution. Most plants can accommodate themselves to a wide range in pH, which depends upon the kind of plant, and upon the conditions to which it has been subjected during its age of adaptation. A blueberry, whose ancestors have been growing for ages in an acid bog soil, should not be expected to have the same characters as those of an alfalfa plant which delights to grow in a limestone soil.

The facts which have been brought out in the foregoing discussion, tend to explain why a farmer often gets better results with mixed fertilizers than he does with applications of single salts. An application of potassium chloride often does more harm than good. An application of sodium nitrate also may have very little effect upon many crops. However, a mixture of potassium chloride and sodium nitrate may increase the crop 100-fold. Such instances have come under the observation of the authors repeatedly. The presence of a mixture of salts saves the plant from much unnecessary expenditure of energy. In this way one plant food may stimulate markedly the absorption of another plant food. This is illustrated in the following table, in which experiment the effect of nitrates upon the absorption of potassium was determined.

TABLE 26.—THE EFFECT OF NITRATES UPON THE ABSORPTION OF POTASSIUM.

No.	Nutrient solution	Grams K in 100 plants	Pct. increase of K absorption over No. 2
1	Distilled water	.0366	—
2	500 p.p.m. KCl	.1435	—
3	500 p.p.m. KCl, 500 p.p.m. $NaNO_3$	.2564	105
4	500 p.p.m. KCl, 500 p.p.m. NaCl	.1432	0
5	500 p.p.m. KCl, 500 p.p.m. NH_4NO_3	.2547	103

The percentage inrcease was obtained by subtracting the potassium content of number 1, which represented the content of the original seed, from all of the others, then calculating the increase in absorption which was caused by the presence of sodium nitrate, sodium chloride, and ammonium nitrate respectively.

The pH of the culture solution of No. 2, which contained potassium chloride only, remained below 6.0, and in such a pH the plant could not operate effectively. The presence of sodium chloride in addition to the potassium chloride did not remedy the situation, as no acid ions were added for which the plant had a strong demand. In the other cultures, sodium nitrate and ammonium nitrate furnished the NO_3 ion which the plant could absorb readily, and thus regulate the reaction.

From all of these results, it is evident that the absorption of nutrient material is controlled largely by the reaction, pH, of the soil solution, and that carbon dioxide, either when generated in the soil by bacteria, or exuded by the roots of plants, is the most effective means of regulating the reaction.

In the humid regions of the East, practically all soils tend to become acid under continuous cutlure, but this is not true in Arizona. Here the tendency is in the opposite direction, and this is caused largely by poor aeration, slow permeability of water, scarcity of organic matter, and the absence of carbon dioxide in the soil.

The tendency of our soils to become more alkaline is shown in an interesting way, in the injurious after-effects of sorghum. It is well known that, following a heavy growth of sorghum, certain soils become puddled and temporarily infertile. In the calcareous soils dispersion, or puddling, is caused by an alkaline reaction. It has been shown in this laboratory (13) that toxic compounds, which are formed in the decomposition of sorghum stubble, destroy most of the aerobic bacteria. While the decomposition is going on, no carbon dioxide is generated in the soil, and the pH rises. This deflocculates the soil and this puddled condition will remain until the decomposition is over, and a new bacterial flora developed and carbon dioxide generated.

Many other interesting observations upon the effects of carbon dioxide upon the penetration of water into black alkali soils have been made. Cold water, saturated with carbon-dioxide gas, will percolate freely almost all dispersed, calcareous soils. Solutions of gypsum will improve percolation, but a solution of sulphuric acid will percolate more freely than an equivalent amount of gypsum. When sulphuric acid is added to a calcareous soil, the acid is neutralized immediately, gypsum is formed, and carbon dioxide liberated. The final product is a solution of gypsum, saturated with carbon dioxide. The increase in the speed of penetration is probably due to the presence of carbon dioxide, which unites with calcium carbonate, and forms soluble calcium bicarbonate. The calcium then replaces sodium in the zeolite and flocculates the soil.

There is still another function of carbon dioxide which is of great interest in Southwestern soils, namely, the part it plays in the solubility of difficultly soluble carbonato-phosphates (13). This compound, a chemical combination of calcium carbonate and tricalcium phosphate, represents the form in which the largest part of phosphate is present in arid, calcareous soils. It is exceedingly insoluble under conditions where carbon dioxide is absent, and calcium carbonate present, but becomes fairly soluble when free carbonic acid is present. The fixation of phosphates as carbonato-phosphate is prevented by the presence of free carbon dioxide.

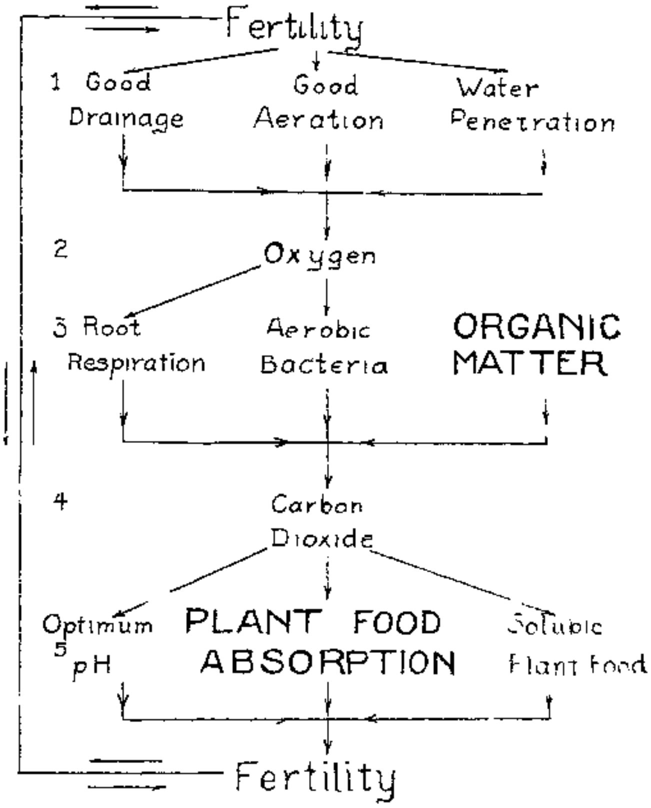

Fig. 5.—A graphical representation and arrangement of the factors which govern the fertility of alkaline soils.

These somewhat unorthodox aspects of fertility in black alkali soils, are presented graphically in Figure 5. All of the factors represented are mutually interdependent, and the chain is no stronger than its weakest link. The following will serve to explain the terms used:

Good drainage.—The maintenance of fresh water in the root zone, and absence of any stagnant water accumulations which tend to become saturated with the root exudations.

Good aeration.—The ready movement of air in the root zone, associated with a soil of good mechanical condition. In other words, fresh air for the roots.

Water penetration.—Practically the same as good drainage.

Oxygen.—Oxygen is vital to all root processes, and all of the above conditions contribute to a good supply of oxygen, upon which the next operations are, in turn, dependent.

Root respiration.—Roots breathe, absorbing oxygen and exuding carbon dioxide, hence the need for, and dependency upon, all of the preceding factors.

Aerobic bacteria.—Oxygen is essential for aerobic bacterial activity which activity, in turn, plays an important role in plant food assimilation. In the absence of oxygen, only those bacteria capable of thriving in the absence of oxygen will be active, and these are antagonistic, as a rule to plant growth.

Organic matter.—Our soils contain so little organic matter that we have indicated this factor as being one to be supplied almost entirely from outside sources. It is the raw material upon which soil organisms thrive, and aid the roots in converting non-available forms of plant food into available forms.

Carbon dioxide.—This factor should be starred in the graph, as it plays the leading role in fertility. It produces desirable soil texture and renders plant food available. Its role is involved closely in the operations of all of the other factors represented in the chain.

Optimum pH.—This factor is almost entirely controlled by carbon dioxide, and its role in the fertility of black alkali soils is deserving of great emphasis.

Soluble plant food.—While this factor may be, in part, controlled by field operations, and the preceding factors which have been cited, it is largely controlled in a practical way by applications of commercial fertilizers.

Absorption of plant food.—A factor which is entirely dependent upon optimum pH, and upon other factors which influence soil reaction.

Fertility may be expressed mathematically as a "vector quantity." It is the resultant of a great many factors, and all these factors are dependent upon, and adjusted to, each other. As the farmer often expresses it. "a soil must work," must be active physically, chemically, and biologically. No soil can produce the best of crops unless all factors, for example such a group as illustrated in Figure 5, are active.

It is the opinion of the authors, and our investigations tend to confirm this, that many fungus and bacterial diseases of plants can be traced directly to malnutrition, or to the failure of the soil to function properly. Certain plant diseases are being overcome by the intelligent use of suitable commercial fertilizers or organic manures. In the animal world, too, it is becoming more and more evident that nutrition plays an important part in susceptibility to disease. For example, roup in fowls has been shown to be a nutritional disease. When a plant is poorly nourished, it becomes a prey to many bacteria or fungi which would probably never attack a perfectly healthy individual.

Some of the factors given in Figure 5 are beyond the control of the farmer but such important links in the chain as good water penetration, aeration, drainage, and application of fertilizer when given proper attention will indirectly tend to promote the functioning of all factors in unison. It is not possible, economically, for a farmer to supply carbon-dioxide gas to his soil, but he can supply the organic matter from which the soil organisms can produce carbon dioxide. Nearly all methods now in common use for reclaiming black alkali soils, such as plowing under manure or other kinds of organic matter, Bermuda grass, etc., are really methods of introducing carbon dioxide into the soil. Leaching, when it can be done satisfactorily, brings on aeration and soil breathing, and stimulates bacterial activity with the production of carbon dioxide.

Carbon dioxide is without doubt the most important factor in the reclamation and fertility of black alkali soils.

CONCLUSIONS

1. Few, if any, black alkali soils contain sufficient black alkali to be directly toxic to plant growth.

2. At pH 10.0, which is a high alkalinity for a black alkali soil, there is only about 1 part per million of hydroxyl ions, which is equivalent to 2.3 parts per million sodium hydroxide, or 7.45 parts per million sodium carbonate. None of these concentrations are considered directly toxic.

3. The complete absence or great deficiency of carbon dioxide in black alkali soils is the greatest factor concerned with the low fertility of many of them.

4. Plants are not able to absorb phosphate or nitrate ions from solutions of greater alkalinity than that represented by approximately pH 7.6.

5. Hydroxyl ions depress, or almost entirely prevent, the absorption of phosphate and nitrate ions by plants.

6. The optimum pH for plant food absorption is near neutrality, or approximately pH 6.8.

7. When plants are placed in nutrient solutions of acid or alkaline reactions, they will gradually adjust the nutrient solutions in the direction of neutrality. The change from alkalinity to neutrality is more rapid than that from acidity to neutrality.

8. The plant absorbs phosphate from solutions of all phosphate salts, at approximately equal rates, regardless of the bases present.

9. Plants absorb phosphates more rapidly from carbonic-acid solutions, than from sulphuric-acid solutions.

10. Plants absorb phosphates more rapidly in the light than they do in the dark.

11. Observations made upon wheat, corn, barley, and tomato plants all show the same effect of pH upon absorption.

12. The absorption of phosphate is slightly, but not seriously, depressed by relatively high concentrations of neutral salts in the soil solution.

13. The rate of transpiration of plants is not affected materially by alkaline reactions up to pH 9.0.

14. Transpiration and ion absorption take place independently.

15. Plant roots will elongate at alkaline reactions where phosphate and nitrate ions are not absorbed.

16. The beneficial effect of an application of manure to a black alkali soil is due largely to the carbon dioxide which is evolved during the process of decomposition.

17. Without doubt, carbon dioxide is the most important single factor in the fertility of alkaline soils.

18. In alkali soil studies, more attention should be given to the consideration of the influence of alkaline soil characteristics upon plant performance.

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